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EVALUATION METHOD OF STRUCTURAL FIRE RESISTANCE

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1.INTRODUCTION

Traditionally, the Building Standards Law of Japan has included a large number of prescriptive requirements in the form of obligatory classification requirements for components and structural elements. The regulation concerned with fire building safety is no exception to prescriptive law. However, the general aim has been expressed explicitly, even if not very clearly. Recently, fire safety code of building is changing from prescriptive to a performance-based approach in several countries. In Japan, for the performance-based approach, the verification tool by way of fire safety design system is just developing.

A case-study was carried out to examine the feasibility of a performance-based fire safety design system developed in Japan. This system would have the capability for leading to flexibility for designing buildings, to deal with new types of materials, elements or buildings etc. Especially, the evaluation method of structural fire resistance was indicated in this report.

2.EVALUATION METHOD FOR DETERMINING STRUCTURAL FIRE RESISTANCE

The evaluation of structural fire resistance is a method by calculation and experiment. The former means a method using simple equations and computer simulation and the latter means experiment by ISO 834 and so on. In this report, a calculation method composed of closed-form equations was shown. As for structural fire resistance of buildings estimated by this system, it is necessary to calculate temperature in fire compartment and service load of structural elements. It is possible to evaluate performance of structural fire resistance by using the result of these calculations. These closed-form equations were developed by Japanese researchers, in order to verify fire safety of building design according to performance based concepts[1]. The formula proposed in this report is as follows:

2.1□Prediction method of Fire Behavior

1 Fuel Surface Area

Fuel carried in buildings can be divided into two types, namely live load and dead load. The surface area of fuel may affect fire behavior within a compartment. As a result of investigations of live load in Japan[2], it was found that its surface area depends on its density, approximately. Namely fuel surface area is given by:

$$\square\ A_{fuel} = 0.214 \times q_l^{1/3} \times A_{floor} + \sum \phi \times A_{fix} \qquad 1)$$

The fuel surface area in this equation indicates the sum of live load and dead load within a fire compartment. In this equation, q_l indicates the heat release rate per unit fuel surface area of live load, □ indicates the oxygen consumption coefficient of dead load. These values were derived from the following tables.

Table 1□ Heat release rate per unit fuel surface area of live load : q_l□

Occupancy	HRR□q_l□MJ/m^2□
Meeting room	160
Seating space of theater and assembly room	240
Guest room of hotel	240
School room	400
Stage of theater and assembly room	480
Selling floor of department store	480
Seating space of restaurant	480
Office room	560
Residential room	720

Table 2□ Oxygen consumption coefficient of dead load :□ □

Class of interior material	Oxygen consumption coefficient □
Noncombustible material	0.1
Fire retardant material□excluding noncombustible material□	0.2
slow burning material□excluding noncombustible material and fire retardant material□	0.4
Material excluding above	1.0

2 Effective Ventilation Parameter

To predict fire behavior, it is important to estimate the rate of air inflow from openings to fire compartment. In regime of ventilation controlled fire, the air inflow rate from openings depends on the size of opening, so-called ventilation parameter. In this estimation method, when there is more than one opening in the walls of a compartment and the height of openings is at the same level, or when there is one opening, the ventilation parameter is derived from the next equation.[3)]

a□In case the height of openings is at the same level, or there is one opening,

$$□\left(A\sqrt{H}\right)_{eff} = \sum_k B_{op,k} H_{op,k} \sqrt{H_{op,k}} \qquad 2□$$

Furthermore, when there is more than one opening in the walls of a compartment and the height of openings is at different levels, the ventilation parameter is calculated from the next equation.

b□In case the opening height is different,

$$\left(A\sqrt{H}\right)_{eff} = \begin{cases} 6.4A_a\sqrt{h_{as}} & (A_a/A_s \le 0.25) \\ 3.2\sqrt{A_a A_s}\sqrt{h_{as}} & (0.25 \le A_a/A_s \le 1.27) \\ 3.6A_s\sqrt{h_{as}} & (1.27 \le A_a/A_s) \end{cases} \qquad 3□$$

where,

$$□\, z_{avg} = \frac{\sum_k z_k B_{op,k} H_{op,k}}{\sum_k B_{op,k} H_{op,k}} \qquad 4□$$

$$\square A_a = \sum_k A_{a,k} ,\square A_s = \sum_k A_{s,k} \qquad 5\square$$

$$h_{as} = \left(\frac{\sum_k A_{s,k}\sqrt{h_{s,k}}}{\sum_k A_{s,k}} \right)^2 + \left(\frac{\sum_k A_{a,k}\sqrt{h_{a,k}}}{\sum_k A_{a,k}} \right)^2 \qquad 6\square$$

3 Combustion Controlled Parameter

Combustion controlled parameter means regnant factor of fire behavior and separates in two regimes, i.e., the ventilation controlled stage and the fuel controlled stage. Fire behavior depends on fuel conditions and opening conditions, namely the fuel surface area and the ventilation parameter, respectively. In this evaluation method, the combustion controlled parameter was derived by dividing the ventilation parameter by the fuel surface area.

$$\square \chi = \left(A\sqrt{H}\right)_{eff} \Big/ A_{fuel} \qquad 7\square$$

4 Heat Release Rate

To investigate the effect of the fuel conditions and ventilation parameter on the burning rate, compartment fire experiments were conducted. As a result, the mass burning rate increases proportionally to the ventilation parameter and well agrees with the relationship given by Kawagoe et al. regardless of the type and the surface area of fuels when the ventilation parameter is small. Moreover, the mass burning rate gradually decreases as the ventilation parameter increases beyond a certain value and asymptotically approaches the free burning rate of fuel[4]. Based on the result, the mass burning rate transformed the heat release rate. It can be expressed as:

$$\square q_b = A_{fuel} \times \begin{cases} 1.6 \times \chi & (\chi \leq 0.07) \\ 0.112 & (0.07 < \chi \leq 0.1) \\ 1.92 \times \chi \times \exp(-11 \times \chi) + 0.048 & (0.1 < \chi) \end{cases} \square\square \qquad 8)$$

□ Total Heat Release of Fuel

Total heat release of fuel is derived from the sum of live load and dead load that is carried in a compartment. The heat release of live load and dead load can be taken from Table 1 and Table 3, respectively. The value of total heat release is estimated by:

$$\square Q_r = q_l A_{floor} + \sum q_{fix} A_{fix} d_{fix} \qquad 9)$$

Table 3□ Heat release rate per area and thickness of building interior material :□fix

Occupancy	HRR q_{fix}□MJ/m^2/cm□
Noncombustible material	8
Fire retardant material□excluding noncombustible material□	16
Slow burning material□excluding noncombustible material and fire retardant material□	32
Material excluding above	80

□ Fire Duration

Fire duration was calculated by dividing by the total heat release by the heat release rate, i.e.:

$$t_f = \frac{Q_r}{60 q_b} \qquad 10)$$

□ Fire Severity Parameter

Fire severity parameter□indicates the inclination of temperature rise within a fire compartment. The greater the value of □, the faster temperature rises. To calculate the fire severity parameter, heat property of fire compartment wall, opening conditions and fuel conditions were taken into consideration. Thus:

$$\square\ \beta = 1280\left(\frac{q_b}{\sqrt{A_T\sqrt{k\rho c}}\sqrt{(A\sqrt{H})_{eff}}}\right)^{2/3} \qquad 11)$$

□ Fire Temperature Curve

Fire temperature curve given by using the fire severity parameter is calculated by the next equation.

$$\square\ T_t = \beta t^{1/6} + T_0 \qquad 12\square$$

As for ISO 834 Standard Fire Temperature Curve(SFTC), the value of □ is approximately 460.

2.2□Structural Stability(under discussion)

1 Critical Temperature of Steel Member

To evaluate structural stability for steel structure buildings, several simplified calculation methods have been developed. Their function is to bridge the gap between element classification according to design plans and elaborate scientific computer models. In present evaluation method, closed-form equations were used to evaluate structural stability. By calculating the steel temperature of a column or beam, it can be determined whether it reaches to the critical temperature or not in a fire, i.e., collapse of most structural components in a fire can be related to the loss of strength at high temperature. The critical temperature of a column or beam is estimated by the next equations.

$$\square\ x(T) = \begin{cases} 1 & : T_R \le T < 300 \\ \dfrac{750 - T}{450} & : 300 \le T < 750 \end{cases} \qquad 13)$$

1) Beam critical mode

$$\overline{q}_A(T) = x(T) \qquad 14)$$

2) Column and beam critical mode

$$\overline{q}_B(T) = x(T)\left\{\frac{1}{2} + \tau\left(\frac{\overline{p}}{x(T)}\right)\overline{Z}\right\} \qquad 15)$$

3) Column critical mode

$$\overline{p} = x(T_c) \qquad 16)$$

where

$$\square\ \overline{q} = \frac{ql^2}{4M_{PB}},\ \overline{Z} = \frac{M_{PO}}{M_{PB}} \qquad 17)\ 18)$$

2 Temperature-time Curve of Steel with Protection Material

If the temperature-time curve for the fire exposure is known, the steel temperature-time of a structural member can be calculated from heat transfer calculations. Thereby, the time until steel achieved critical temperature can be estimated. On the other hand, the critical time can be also evaluated by fire tests. Equations conducted by experiment results obtained from ISO 834 Fire Tests were used in this method.

$$□t_{C,ISO} = a_0\left(\frac{1}{H_{si}/A_{si}} + a_1\right)(d_i + a_2)(T_{C,ISO} + a_3) + a_4 \qquad 19□$$

a)Rock wool□a_0=0.2331,a_1=0.0096,a_2=13.9764,a_3=404.7274,a_4=-50.2965□($57<H_s/A_s<196$)
b)Calcium silicate board a_0=1.427802,a_1=-0.00095,a_2=-3.41117,a_3=-82.2283,a_4=-28.43666□($57<H_s/A_s<196$)

As the above equations correspond to the ISO 834 SFTC (fire severity parameter□=460), by way of enabling application to different parameter □, the temperature-time curve was derived by below equation[5].

$$□t_{f,ISO} = 1.2\left(\frac{\beta}{460}\right)^{3/2} t_f \qquad 20)$$

2.3□Evaluation of Structural Stability

If critical time of structural member ($t_{C,ISO}$) is longer than fire duration time($t_{f,ISO}$), building structural member may remain stable. Conversely, if critical time of structural member is shorter than fire duration time, modification of insulation etc. is required.

3.CASE-STUDY

In a sense, the calculation methods are intended to give data in order to replace fire test results. As regards evaluation of structural elements, simplified calculation methods are assumed to provide a level of safety equal to or better than prescriptive requirements. However, the safety level of its method is not actually well known. Then, case study using this evaluation method was carried out.

3.1 Conditions

The following types of buildings were used:
a)Apartment house, b)Hotel, c)Office(office room), d)Office(meeting room), e)Retail shopping, f)Hospital(sickroom), g)School, h)Exhibition hall

For calculation purposes, building features, i.e., floor area, height and wall surface area of room, opening width and height etc. were taking from building plans.

3.2 Results

The case study was carried out from about 80 building plans. First, the example of a case study using this evaluation method is shown in detail. The type of building is an office.

3.2.1 Calculation conditions

Figure 1 shows office building plan as the object of the case study and Table 4 indicates the required conditions necessary to calculate by closed-form equations under the building plan.

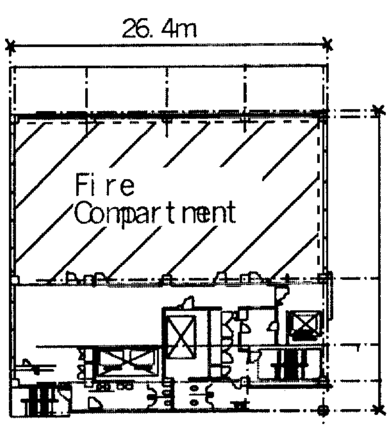


Table 4 Calculation conditions

1) Compartment /Opening etc.

Compartment	Width	26.1m
	Depth	13.9m
	Height	2.7m
	Inside wall area	941.6m^2
	Spandrel height	2m
Opening	Width	20m
	Height	1.9m
Fuel Density		35kg/m^2
Ambient temperature		293K

Figure 1 Office building plan

Table 4 Calculation conditions

2) Beam/Column

Beam (H-700*250*14*28)	
Sectional area	0.0232 m^2
Plastic section modulus	0.006155 m^3
Section modulus	0.005409 m^3
Moment of second order	0.00189306 m^4
	0.00007306 m^4
Radius of gyration	0.056 m
Width-thickness ratio of flange	4.2
Width-thickness ratio of web	46
Thickness of calcium silicate board	0.03 m

Column (H-600*600*32)	
Sectional area	0.0674 m^2
Plastic section modulus	0.015502 m^3
Section modulus	0.013073 m^3
Moment of second order	0.00392175 m^4
Radius of gyration	0.232 m
Width-thickness ratio of flange	18.8
Compartment height	3.9 m
Slenderness ratio	16.8
Thickness of calcium silicate board	0.03 m

□

3.2.2 Fire room temperature and fire duration time

The temperature-time curve in fire compartment can be simulated by closed-form equation. Figure 2 and Table 5 indicate results comparing prediction result with ISO 834 SFTC on fire duration time and peak of temperature.

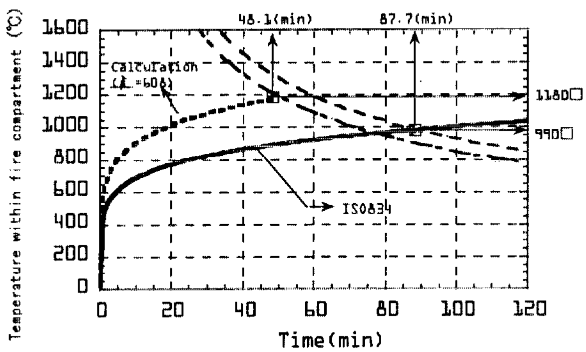


Figure 2 Temperature-time curve

Table 5 Fire duration time and fire maximum temperature

Fire duration time(t_f)	48.1min
Fire maximum temperature($T_{f,max}$)	1180□
Fire duration time by ISO834($t_{f,ISO}$)	87.7min
Fire maximum temperature by ISO834($T_{f,max,ISO}$)	990□

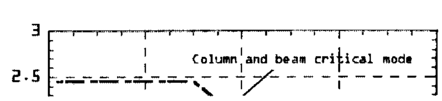
As can be seen in Figure 2, the temperature rise predicted by closed-form equations is higher than the ISO 834 Standard Fire Temperature Curve. In short, fire severity parameter □ is larger than ISO 834.

3.2.3 Structural stability

The structural stability of steel structure buildings was estimated by closed-form equations based on 'Simple Plasticity Theory'. By using these equations, it was possible to evaluate the temperature of steel columns and/or beams, and whether it would reach to the critical temperature or not.

Figure 3 shows steel temperature-time curves of a column and a beam, respectively. From the calculation result given in Figure 3, maximum temperature of the column and the beam is 195 □ and 414 □, respectively.

Using maximum steel temperature of column and beam, structural stability can be estimated as



shown in Figure 4. Consequently, it is found that steel structures stabilize against fire from estimation of this case study.

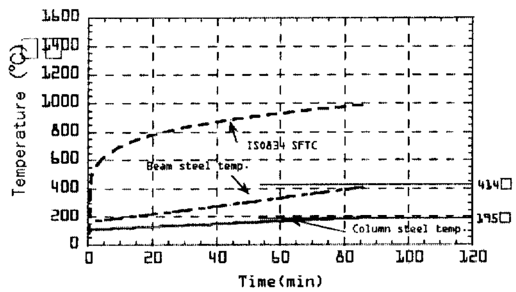


Figure 3 Calculation result of steel temperature of column and beam

4.CONCLUSION

In this report, the evaluation method composed of closed-form equations and results of case-study by its method was indicated. The case study shown in this report only exemplifies rigid frame structure type. It is necessary to carry out further case studies about other structure types.

SYMBOL

A: opening area (m^2), A_a: lower opening area(m^2), A_{fix}: surface area of building interior material(m^2), A_{fuel}: fuel surface area(m^2), A_{floor}: floor area (m^2), A_s: upper opening area(m^2), A_{st}: cross section area of steel(m^2), A_T: surface area of compartment inside wall (m^2), B_{op}: opening width(m), c: specific heat(kJ/kgK), d_i: thickness of insulation(mm), d_{fix}: thickness of building interior material(m), H: opening height(m), H_a: lower opening height(m), H_{op}: opening height(m), H_s: upper opening height(m), H_{st}: perimeter length of steel(m), k: heat conductivity(kW/mK), q_{fix}: heat release rate per unit area and unit thickness of building interior material ($MJ/m^2/cm$), q_l: heat release rate per unit surface area of live load(MJ/m^2), t: time after fire occurrence(min), $t_{C,ISO}$: critical time of steel heated by ISO834 standard fire curve(min), $T_{C,ISO}$: critical temperature of steel(°C), T_0: ambient temperature(=20)(°C), ρ: density(kg/m^3)

REFRENCE

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